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LOW-ORDER BLADE MODELING FOR COMPRESSOR AEROELASTICS

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6. AUTHORS

Petar V. Kokotovic
James D. Paduano

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Electrical and Computer Engineering
University of California, Santa Barbara
Santa Barbara, CA 93106-9560

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13. ABSTRACT *(Maximum 200 words)*

To incorporate blade-row unsteady aerodynamics into system-level flutter and forced response models, a frequency-domain Proper Orthogonal Decomposition was applied to an Euler CFD code which incorporates motion of an unstructured grid. With Arnoldi vectors as input-output generalizations of the basis functions, an efficient model order reduction procedure is developed and applied to a typical transonic rotor. These results helped incorporate model-order reduction procedures into the aeroelastic design and analysis procedures of Pratt & Whitney.

In the second part of this effort low-order compressor models, are used to design static nonlinear controllers to suppress rotating stall, and thus extend the stable operating range of the compressor. New nonlinear controllers may introduce beneficial bifurcations and create the possibility of stabilizing optimal operating regimes with reduced control effort.

14. SUBJECT TERMS

Unsteady aerodynamics, system-level flutter, Proper Orthogonal Decomposition, model order reduction,
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University of California, Santa Barbara
Center for Control Engineering and Computation
Department of Electrical and Computer Engineering
Santa Barbara, CA 93106-9560

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LOW-ORDER BLADE MODELING
FOR COMPRESSOR AEROELASTICS

submitted to

AFOSR/NA
ATTN: AASERT Program
801 N. Randolph Street
Arlington, VA 22203-1977

PRINCIPAL
INVESTIGATORS: Petar V. Kokotovic
James D. Paduano

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INTRODUCTION

The grant reported on here was an augmentation to the cooperative PRET program between UCSB, UC Davis, Caltech, MIT, and UTRC, entitled "Robust Nonlinear Control of Stall and Flutter in Aeroengines". The original purpose of the effort was to eliminate the computational barriers to incorporating blade-row unsteady aerodynamics into system-level flutter and forced response models. This goal has been achieved using a unique frequency-domain application of Proper Orthogonal Decomposition to an Euler CFD code which incorporates motion of an unstructured grid [1,2]. Arnoldi vectors, which are input-output generalizations of the basis functions found using Proper Orthogonal Decomposition, were found to achieve even more efficient and accurate models [3]. These model order reduction procedures were applied to a typical transonic rotor, and the importance of low order modeling for various system-level studies of flutter and forced response, as well as control, was demonstrated [4]. In addition, full-rotor, non-axisymmetric models generated using the procedure (and available by no other means) were used to study mistuning in a collaborative effort with Caltech [5]. These results helped to motivate a new initiative at UTRC to incorporate model-order reduction procedures into the aeroelastic design and analysis procedures of Pratt & Whitney [6]. Further details on these and other accomplishments are outlined in Part I of this document and expanded upon in the attached papers.

The research goal was extended to include another important aspect of low order modeling. The second part of this report describes further progress in designing controllers based on the low-order compressor models, developed earlier in the PRET program. These static nonlinear controllers suppress rotating stall, and, thus, extend the stable operating range of the compressor by altering the fundamental nature of the dynamics near the optimal operating condition at the peak pressure rise of the compressor. The properties of dynamic nonlinear controllers, however, have not been fully investigated. Our current results indicate that nonlinear controllers that introduce additional dynamics may introduce beneficial bifurcations and create the possibility of stabilizing optimal operating regimes with reduced control effort. This work is described in our papers [9-12] and briefly summarized in Part II of this document.

Part I

LOW-ORDER BLADE PASSAGE MODELING FOR COMPRESSOR AEROELASTICS

James D. Paduano **Karen Willcox** **James Peraire**

Gas Turbine Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

Objectives

The original objective was to develop CFD-based, low order, nonlinear dynamical models of blade passage unsteady aerodynamics and flutter; to compactly represent the input-output characteristics of a blade passage in transonic flow with moving blades, and to couple these models to structural-dynamic and system-level flutter models for use in control, system identification, and flutter modification studies. Discussions with industry experts, and experience gained during the program, led us to modify this objective in two ways. First, it is generally agreed that the aerodynamics behave linearly over the displacement and incidence conditions experienced in modem gas turbine engines. Also, the computational burden associated with computing the nonlinear unsteady blade row response is significantly higher than that associated with the linearized response. Therefore, CFD-based, low-order, linear dynamical models were sought. The second modification to the goals was that, rather than incorporating the blade passage models into system level models, we found that actually creating *whole rotor* flowfield models, as building blocks for system level models, directly from the low-order modeling results was more consistent with the formulation and boundary conditions. System instabilities, such as rotating stall and surge, can then be obtained simply by applying the proper boundary conditions to these whole-rotor building blocks.

Accomplishments/New Findings

The main accomplishment of this research was the creation, implementation, and demonstration of a complete procedure that starts from a compressor blade geometry, computes the unsteady forces on the blade over the desired range of interblade phase angle, reduced frequency, and operating conditions, and encapsulates all of this information into a low-order model. The resulting model is in standard state-space form, and typically requires 10 to 20 states per interblade phase angle, compared to ~10,000 states in the CFD computation. It is also significant that the computational model, and the resulting low-order model, are formulated as input-output systems, whose inputs include the structural motions and the aerodynamic boundary conditions. Incorporation of boundary conditions as inputs and outputs allows multiple blade rows to be stacked together (as in a transmission matrix analysis), upstream disturbances to be modeled, etc. This represents a significant departure from typical aeroelastic analyses, which assume non-reflecting boundary conditions. It is becoming increasingly apparent that the assumption of non-reflecting boundary conditions can significantly effect aeroelastic predictions. The modeling methods developed in this program directly address this issue,

New findings can be separated into two groups -- those related to reduced-order modeling theory, and those which relied on the models to investigate flutter and forced response solutions. In the area of reduced-order modeling, it was shown that blade row aerodynamics can be efficiently represented using a very small number of states (this result needs to be extended to CFD models which include viscous losses). The models are best broken up by interblade phase angle (circumferential mode number), but a wide range of frequencies of excitation can be captured using relatively few states. There is also evidence that the models could capture useful ranges of operating conditions (interblade phase angle, Mach number, etc.) if appropriate CFD experiments are utilized. The use of frequency-domain Proper Orthogonal Decomposition, and its relationship to the Arnoldi method for choosing basis vectors of large-scale linear systems, was discovered and elucidated.

By applying these models to various flutter and forced response problems, several important results were obtained. First, in collaboration with Caltech, it was shown that

the concept of 'Robust Mistuning' is indeed a viable one for improving the flutter and forced response properties of compressor rotors. Robust mistuning augments the classical concept of increasing aeroelastic damping by slight variation of rotor blade properties (usually natural frequency) over the rotor. The optimum pattern of blade mistuning must be robust to uncertainty in the blade natural frequency to prevent 'rogue blade' type instabilities. To test robust optimization procedures, one needs a full-rotor model, which is much too intensive for CFD procedures. Using low-order models, however, the optimization was demonstrated. Experiments at NASA Glenn will experimentally investigate this idea.

Low order models were also used to illustrate the error introduced by using assumed frequency methods to compute forced response characteristics. In transonic rotor trial case, blade displacements were underpredicted by ~26%, and worst-case frequencies were off by ~15%. Such characterization of prediction error is only possible using reduced-order modeling, and should prove valuable to engine designers in the future. Finally, it was shown using a subsonic test case that bringing a rotor into close proximity with a stator (instead of assuming non-reflecting boundary conditions) can destabilize the rotor, decreasing the damping ratio by 2% for some interblade phase angles. The input-output formulation of the low-order model allowed this result to be obtained systematically.

Part II

LOW-ORDER COMPRESSOR MODELING AND ACTUATOR-INDUCED BIFURCATIONS

Petar V. Kokotovic   Michael Larsen

Center for Control Engineering and Computations
Department of Electrical and Computer Engineering
University of California
Santa Barbara, CA 93106-9560

Objectives

The original goal of this project was extended to include another unexpected effect of low-order models—that of actuator-induced bifurcations. This bifurcation was discovered during a study of the effects of actuator constraints on the performance of the static nonlinear controllers developed in the PRET research effort for the control of rotating stall and surge in compressors. Simulations of one of the controllers with an actuator lag on the low-order Moore-Greitzer model yielded surprising results: rotating stall was suppressed with less control effort than in the low-order model without actuator dynamics. This motivated us to pursue a detailed bifurcation analysis to explain this unusual behavior and determine the robustness of the phenomenon.

Accomplishments/Findings

The main accomplishment of this research was the discovery and analysis of a new bifurcation induced by a dynamic nonlinear controller for the control of rotating stall. The controller stabilizes a small limit cycle resulting in a stable average-optimal operating condition around the peak of the compressor characteristic, while eliminating rotating stall. This is in contrast to previous static nonlinear designs, which achieve

performance improvement by only reducing rotating stall. Whereas these controllers stabilize an operating point on the rotating-stall characteristic with steady non-axisymmetric flow, the new dynamic controller stabilizes an unsteady axisymmetric operating regime at peak pressure rise. At the same time, the bifurcation phenomenon allows the controller to employ smaller control effort.

Personnel Supported

Eric Nelson, Masters Student

Gordon Maahs, Masters Student

Michael Larsen, PhD Student.

Publications/References

[1] Willcox, K. E., "Reduced-Order Aerodynamic Models for Aeroelastic Control of Turbomachines" Ph.D. Thesis, Massachusetts Institute of Technology, February 2000.

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[3] Willcox, K., Peraire, J., and White, J., "An Arnoldi Approach for Generation of Reduced Order Models of Turbomachinery," Submitted to the 38th Annual Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2000.

[4] Willcox, K., Peraire, J., and Paduano, J., "Application of Model-Order Reduction to Compressor Aeroelastic Models for Turbomachinery", Submitted to the ASME Turbo Expo, Munich Germany, May 2000.

[5] Shapiro, B., and Willcox, K., "Analyzing the Mistuning of Bladed Disks by Symmetry and Reduced-Order Aerodynamic Modeling," Submitted to the Journal of Engineering for Gas Turbines.

[61 Personal communication with UTRC employees.

[7] Greitzer, E. M., Paduano, 1. D., Epstein, A. H., and Weisshaar, T. A., "Basic Research Issues in Aerodynamics, Structural Dynamics, and Control of Turbine Engine High Cycle Fatigue," International Mechanical Engineering Congress, Atlanta, GA, November 17-22, 1996.

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[10] B. Coller and M. Larsen, "Beneficial actuator-induced bifurcations in compressor control," Proceedings of the 37th American Control Conference, Philadelphia, Pennsylvania, 1998, pp. 1994-1995.

[11] R. Sepulchre and P. Kokotovic, "Shape Signifiers for Control of a Low-Order Compressor Model," IEEE Transactions on Automatic Control. 1998, vol. 40, no. 11, pp. 1643-1648.

[12] M. Larsen and P. Kokotovic, "Manifold Placement Designs," UCSB CCEC Technical Report CCEC 99-05-03.

Interactions/Transitions

a. Participation/presentation and meetings, conferences, seminars, etc. (see above for conference presentations)

"CFD/POD Approaches to Modeling Flutter" Progress report at annual PRET meeting on Robust Nonlinear Control of Stall and Flutter in Aeroengines, Santa Barbara, January 30, 1997.

"Overview of Research in Compressor Stability and Aeroelasticity,' Presented at GE Aircraft Engines, Cincinatti, April 28, 1997.

"Off-Blade Prognostic Methods for Aeroelastic Resonance," Presented at GE Aircraft Engines, Cincinatti, October 14, 1997.

"Modeling and System Identification of Compressor Aeroelasticity," Presented at the AFOSR Workshop on Dynamic Systems and Control, Pasadena, May 29, 1998

"From Concept to Experiment: an Active Rotor for Flutter Research,"

Invited Talk, North Eastern Drafting and Data Management Association, May 19, 1999.

"Reduced-Order Aerodynamic Models for Aeroelastic.Control of Turbomachines," Presented to UTRC, July 21, 1999

"Reduced-Order Modeling of Flutter in Turbomachinery," Institute for Engineering Thermophysics, Beijing, October 10, 1999.

"Actuator-Induced Bifurcations," presented at the annual PRET meeting on Robust Nonlinear Control of Stall and Flutter in Aeroengines, Santa Barbara, January 30, 1997.

b. Consultative and advisory functions to other laboratories and agencies

James Paduano - Consultant to UTRC, May-September 1999

James Paduano - Visiting Professor at the Institute for Engineering Thermophysics (Gong Zen Ri Wu Li Suo) and at Beijing University of Aeronautics and Astronautics (Bei Hang) during October, 1999; Sponsored by the Chinese Academy of Sciences.

c. Transitions

Provided information concerning improvements to low order modeling of flutter to Dr. Scott Copeland of UTRC. This transition occurred at the AFOSR contractors review on May 23, 1997 in Dayton, Ohio, and through subsequent phone conversations and mail.

Distributed Master's thesis "System Modeling and Control Studies of Flutter in Turbomachinery" to UTRC and AFOSR-PRFT collaborators.

Worked collaboratively with Ben Shapiro and Caltech to demonstrate robust mistuning concepts using a CFD-based transonic rotor model developed using model-order reduction methods. This work is continuing in demonstrations at NASA Lewis.

Current initiative at UTRC to develop in-house capability in model order reduction for flutter were motivated largely by K. Willcox presentation August 1999.

Work during the summer of 1998 by Michael Larsen at Ford Motor Co. to investigate whether similar bifurcation phenomenon occurs in new types of diesel engines with turbochargers.